



**QUEEN'S
UNIVERSITY
BELFAST**

Combining draping and infusion models into a complete process model for complex composite structures

Pierce, R., Falzon, B. G., & Thompson, M. C. (2015). *Combining draping and infusion models into a complete process model for complex composite structures*. Paper presented at ICCM20 20th International Conference on Composite Materials, Copenhagen, Denmark.

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
[Link to publication record in Queen's University Belfast Research Portal](#)

Publisher rights
© 2015 The Authors

General rights
Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

COMPLETE PROCESS MODEL FOR MANUFACTURING COMPLEX COMPOSITE STRUCTURES WITH FABRIC REINFORCEMENTS

Robert S. Pierce¹, Brian G. Falzon² and Mark C. Thompson³

¹Department of Mechanical and Aerospace Engineering, Monash University
Clayton Campus, Melbourne, Victoria 3800, Australia
Email: robert.pierce@monash.edu

²School of Mechanical and Aerospace Engineering, Queen's University Belfast
BT9 5AH, United Kingdom
Email: b.falzon@qub.ac.uk

³Department of Mechanical and Aerospace Engineering, Monash University
Clayton Campus, Melbourne, Victoria 3800, Australia
Email: mark.thompson@monash.edu

Keywords: Draping, Fabrics/textiles, Infusion, Numerical modelling, Liquid Composite Moulding

ABSTRACT

The simulation of Liquid Composite Moulding (LCM) processing is becoming increasingly important due to growing demand for large, complex and low-cost composite aerostructures. This research combines work from a range of disciplines in order to demonstrate a Complete Process Model (CPM) for LCM manufacturing with textile reinforcement materials. Experimental characterisation of a carbon fibre plain weave fabric provides detailed tensile, shear and permeability properties for use in numerical draping and infusion models. By combining shear deformation results from an Abaqus draping model with deformation-dependent permeability properties, a detailed distribution of flow properties can be defined for the ANSYS Fluent infusion model. This innovation is validated against full-scale, complex vacuum infusion experiments, and demonstrates a significant improvement over traditional modelling approaches.

1 INTRODUCTION

The commercial aerospace industry is driving demand for lighter, cheaper, larger and more complex composite structures. In many cases, this is prompting a transition from traditional autoclave manufacturing techniques to Liquid Composite moulding (LCM) methods and textile reinforcement materials. For LCM processes, the dry reinforcement is typically formed on a tool before infiltration, flow and cure of a liquid resin system. Although this approach is less expensive than autoclave manufacturing, and still delivers high quality parts, these methods remain reliant on operator skill and experience through empirical practices. Subsequently, a significant amount of wasted material and labour often results from the iterative development of large and complex composite structures.

In order to better anticipate production issues, improve production times and lower overall costs, considerable efforts are being made to simulate the LCM manufacturing process. There are three main areas of research that contribute to LCM process modelling: material characterisation (for mechanical [1-7] and permeability [8-14] properties), drape modelling [15, 16] and infusion modelling [17-21].

Despite extensive research in each of these fields, and the well-documented need for a complete simulation package [22, 23], no comprehensive process model to simulate LCM manufacturing has been previously demonstrated. Hence, this paper introduces a Complete Process Model (CPM) that can calculate dry fabric deformation and its effect on infusion for an improved prediction of entire LCM processes.

2 COMPLETE PROCESS MODEL

Fundamentally, a draping model is required to predict the material deformation during forming and an infusion model is necessary to simulate the subsequent resin flow through the material. However, the accuracy of these models also depends on detailed material characterisation. The tensile and shear properties of the preform material support the draping model, and deformation-dependent permeability properties facilitate the link between the draping and infusion stages. The composition of the CPM is visualised in Fig. 1. In the following sections of this paper, the individual CPM components are addressed in greater detail before a final validation of the working CPM is demonstrated.

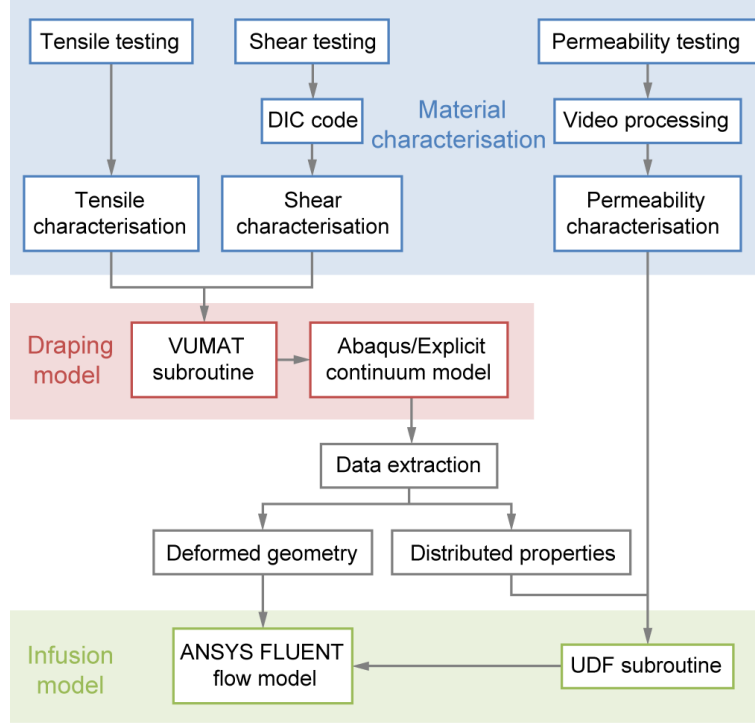


Figure 1: Flow diagram of the Complete Process Model (CPM).

2.1 Material characterisation

Characterisation of the preform behaviour is essential to the accuracy of subsequent modelling efforts. For the CPM demonstration developed in this research, an aerospace grade carbon fibre fabric has been selected as the preform material. This material is a dry plain weave fabric with 3K tows and an areal density of 0.193 kg/m². The tensile, shear and permeability properties of this material have all been characterised experimentally, as previously described in literature [8].

2.1.1 Tensile properties

Since there is no standardised method for the biaxial tensile testing of fabric materials, despite the biaxial nature of the material [1], a uniaxial strip test method (ASTM D035-11) [24] was employed for this research. Tests were conducted on an Instron 4505 frame with updated 5500R electronics, using a 5 kN load cell, under a 0.5 mm/min Constant Rate of Extension (CRE) control. Ultimately, there was negligible difference in the warp and weft strain results, with tests proving to be highly repeatable. Thus, the near-linear tensile response of the fabric in both directions was approximated according to Eqn. (1).

$$E_{11} = E_{22} = 15000 \text{ MPa} \quad (1)$$

2.1.2 Shear properties

Although the importance of fabric shear behaviour for draping is well known, there are no standard methods for textile shear characterisation [2]. In this case, the bias extension test [3, 4] was employed, along with an optical strain measurement technique for greater accuracy. Samples were cut with a gauge region of 100 x 50 mm, with the long testing direction bisecting the warp and weft yarn directions. Tests were run under a 10 mm/min CRE control on an Instron 5948 MicroTester machine with a 0.1 kN load cell. A digital camera was used to record images of samples at regular time intervals. These images were then passed on to a custom Digital Image Correlation (DIC) code in Matlab which calculated the strain behaviour throughout each sample [5]. Shear angles from the central shear zone were averaged in order to calculate the shear modulus and an exponential function for the shear modulus was determined, as shown in Eqn. (2).

$$G_{12} = 0.008196e^{4.24\gamma} + 1.056 \times 10^{-11}e^{23.69\gamma} \text{ MPa} \quad (2)$$

2.1.3 Permeability properties

Despite significant research and several summary papers [9, 10], there remains no standardised method for textile permeability characterisation. Coordinated benchmarking efforts have revealed a great degree of variability in permeability testing, in some cases similar experiments have produced results that vary by an order of magnitude [9]. For this research, since material deformation changes the internal textile architecture, these properties also need to be characterised in relation to fabric shearing [11-14].

An unsaturated radial flow experiment was employed for this work [8], since it allowed for two-dimensional permeability characterisation where the principal permeability directions were not known prior to testing. The permeability tests were conducted under a vacuum-driven constant injection pressure, in batches of at least six samples for fabric shear angles ranging from 0° to 40°. Single plies of the carbon fibre plain weave (300 x 300 mm) were sandwiched between two thick transparent plates. Through-thickness and gravitational effects were neglected due to the thinness of the single ply samples, and a 3 mm radius inlet was used to introduce oil into the samples. Video footage from testing was processed using an in-house Matlab code (accessible online) [25], in order to calculate the directional permeability properties of each sample.

From these experiments, a detailed profile for deformation-dependent permeability behaviour was determined. As shear angles increased, K_1 principal permeability values increased, K_2 principal permeability values decreased and subsequently the permeability anisotropy greatly increased. However, further calibration of the data was required for the Complete Process Model (CPM) due to experimental differences between the permeability and demonstration tests. The final properties used in this demonstration (including the principal permeability direction, ϕ) are outlined in Eqns. (3) - (5).

$$K_1 = (-4.449\gamma^4 + 8.898\gamma^3 - 5.637\gamma^2 + 1.608\gamma + 0.404) \times 10^{-10} \text{ m}^{-2} \quad (3)$$

$$K_2 = (-3.850\gamma^4 + 7.330\gamma^3 - 4.631\gamma^2 + 0.803\gamma + 0.266) \times 10^{-10} \text{ m}^{-2} \quad (4)$$

$$\phi = \begin{cases} \frac{|\gamma|}{20^\circ} \left(45^\circ - \frac{|\gamma|}{2} \right) & \text{if } |\gamma| \leq 20^\circ \\ 45^\circ - \frac{|\gamma|}{2} & \text{if } |\gamma| > 20^\circ \end{cases} \quad (5)$$

2.2 Draping model

The purpose of the draping model is to predict fabric deformation behaviour for both the overall part shape and the distribution of internal shearing. Fabric shear behaviour is well known to be the primary deformation mode for textile materials [7], since yarns are able to move and rotate relative to one another during deformation. Hence, accurate yarn tracking is particularly important for the determination of shear strain, which is typically quantified by the ‘shear angle’, the relative angular change between warp and weft yarns.

In this work, a hypoelastic continuum-based finite element approach has been employed within Abaqus/Explicit, based on previous successful demonstrations [15, 16]. With this method, fabric layers are represented as continuous sheets of M3D4R membrane (or S4R shell) elements, and a VUMAT material subroutine is used to replicate the internal deformation behaviour.

2.3 Infusion model

The infusion model aims to predict resin flow behaviour, assess flow front propagation and predict ultimate fill time of the desired manufacturing process. However, these typically assume a homogenous or isotropic flow through the preform material [17, 18] that is unreliable for complex structures since fabric deformation is known to have an effect on local permeability properties [13, 23]. Subsequently, this work focusses on the significance of deformation-dependent permeability behaviour within infusion for the CPM. At this stage, saturation and compaction effects are largely neglected, and isothermal conditions are assumed, though future consideration of these factors is not outside the capability of the presented infusion model.

Fundamentally, the infusion model employed in this research is based on a Eulerian-Eulerian Volume of Fluids (VOF) approach in ANSYS Fluent. Resin and air phases are treated as interpenetrating continua where the volume of one phase cannot be occupied by any other phase. The volume fractions of the two phases are traced through the domain cells and are used to calculate cell-averaged properties within a common flow field. Therefore, only one set of governing equations needs to be solved for the two phases.

2.4 Combining CPM components

To this point, each of the individual components can be considered as independent. However, in order to more realistically simulate the LCM manufacturing process, all components are combined in contribution to the Complete Process Model (CPM) according to Fig. 1.

Due to incompatibilities between Abaqus and ANSYS Fluent, the linking of the two models is performed in two stages. First, the Abaqus draping results are extracted and exported using a Python script related to the Abaqus Scripting Interface. A ‘deformed geometry’ file is generated to contain all the nodal position data such that remodelling can be performed in ANSYS, and a ‘distributed properties’ file is created for the shear angle and material orientation results associated with elemental locations.

Secondly, upon initialisation of the infusion model, a User Defined Function (UDF) subroutine reads the ‘distributed properties’, stores them, and calculates direction vectors, permeability values and porosity values based on the results of the permeability characterisation experiments. These flow properties are assigned, cell-by-cell, across the modelling domain and result in a more realistic flow field within the deformed material.

3 DEMONSTRATION

In order to validate the Complete Process Model (CPM) and demonstrate its potential, Vacuum Infusion (VI) experiments were performed for a large and complex preform. The double dome

geometry used in this work was a natural choice, as it has been commonly used to evaluate the performance of draping models [15, 16].

3.1 Experimental case

Based on the established double dome geometry [15], a male tool was constructed from structural foam and given an impermeable coating. This tooling was then recessed 120 mm into an outer frame (950 x 550 mm), such that the top of the male tool was flush with the top of the outer frame (Fig. 2).

Single plies of the carbon fibre plain weave material were cut at different orientations, placed over the mould and covered with a vacuum bag. Only the results for test samples with 90°/0° warp/weft yarn orientations are shown in this paper (for brevity), though similar tests were also conducted with -45°/45° and 0°/90° orientations. Each sample was marked with a 50 mm grid of silver lines to facilitate optical measurements from forming and infusion.

Experiments were carried out by first drawing a vacuum through a single, central, outlet port to initiate the bag and preform deformation. Once the preform and bag reached the bottom of the mould, the central outlet was closed-off, and secondary vacuum ports at the ends of the mould were activated (by puncturing tubing through the vacuum bag into each port). After checking bag conformity from the forming stage, the central port was then connected to an oil reservoir to become the fluid inlet for the infusion stage. Throughout the experiments, temperature and pressure were monitored in addition to regular digital imaging of the forming and infusion behaviour. This two-stage process is depicted in Fig. 2.

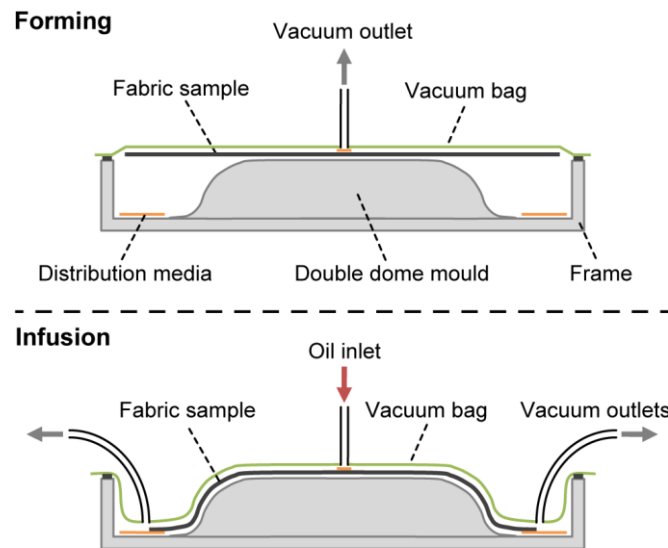


Figure 2: Two-stage process for the double dome demonstration experiments.

3.2 Modelling details

The same demonstration case was replicated with draping and infusion stages using the CPM, incorporating the detailed material properties from experimental characterisation.

The draping model was set up in accordance with previous double dome forming simulations [15, 16], where the fabric blank was modelled in quarter symmetry from approximately 1000 M3D4R membrane elements in Abaqus/Explicit. The tensile and shear properties from Eqn. (1) and Eqn. (2) were included in the VUMAT subroutine for the draping model, and a global contact condition for tangential friction (0.15) was applied across the model. The results from Abaqus were then extracted using the automated Python script to produce the deformed geometry and distributed properties files compatible with the ANSYS Fluent infusion model.

The infusion modelling stage required that the double dome geometry be regenerated in the ANSYS suite, before a 50 mm diameter central inlet was cut from the material (reflective of the inlet). Due to the symmetry of the models, a single outlet condition was applied to one end of the material domain and all other faces (excluding the inlet) were defined using symmetric (free-slip) wall conditions. Inlet and outlet pressures were set to 101.3 kPa and 0.3 kPa respectively. The undeformed base porosity was 0.724 and the oil viscosity was 0.0756 Pa.s. The distributed porosity, principal permeability values (K_1 and K_2) and directions (ϕ) were all defined on a cell-by-cell basis by the UDF subroutine in relation to several properties: the shear angle distribution from draping, the local material directions from draping and the experimentally characterised permeability functions from Eqns. (3) - (5).

The infusion simulations were run with similarly sized meshes of around 1000 elements, and a constant 1 second time-step for 2500 seconds. Mesh convergence, time-step dependence and convergence criteria were all studied to determine these parameters, as a balance of solution time and accuracy. Flow front predictions under these parameters exhibited less than 2% variance from the mesh and time-step independent results. Fig. 3 depicts the modelled boundary conditions for the quarter symmetry 90°/0° case, with illustrations of the distributed K_2 principal permeability vectors and the shear angle contours defined by the draping model.

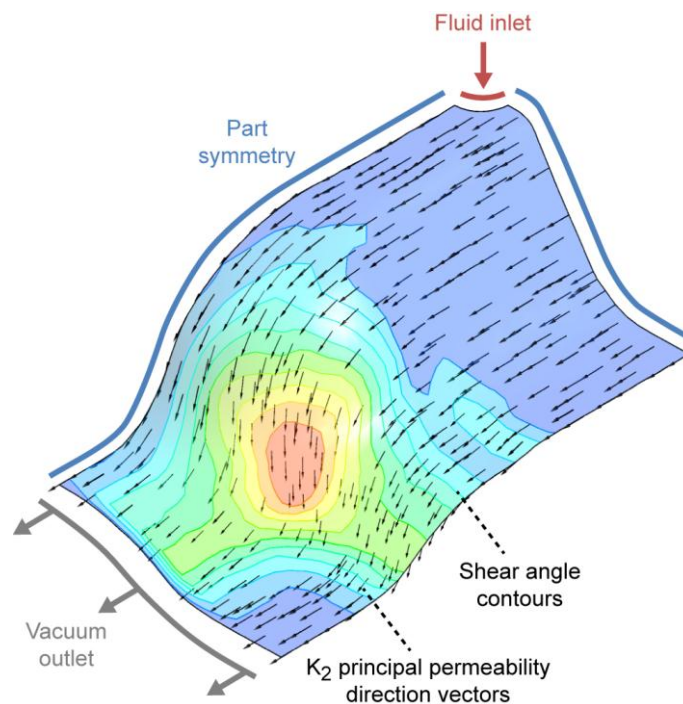


Figure 3: Example of the 90°/0° infusion modelling case within ANSYS Fluent.

3.3 Draping results

A first look at the draping results from the demonstration case reveals that the fabric material conforms very well to the complex mould without any wrinkling (Fig. 4). There was also good symmetry in the experimental forming cases, with only minor yarn fraying at the sample edges. An initial comparison of the material ‘draw-in’ (simply the observed movement of the material from its undeformed state), showed that the grid positions predicted by the CPM were within 2% of the mean experimental results.

The fidelity of the CPM draping simulation was further evaluated by comparing predicted shear angle values across the fabric samples against experimental shear angle results. Overall the predicted

shear angles within each grid square showed very good agreement with the experimental results. For example, shear angle values for 16 locations in the 90°/0° case are shown in Fig. 5. Here, the experimental values are mean results from all symmetrical quadrants of repeated tests, with error bars depicting the standard deviation.



Figure 4: Formed 90°/0° double dome sample.

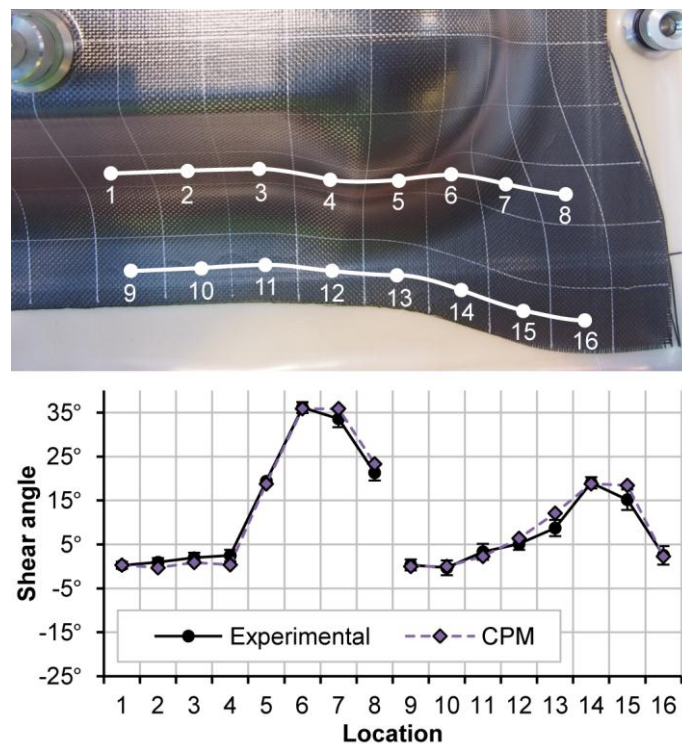


Figure 5: Shear angle comparison for the 90°/0° case.

3.4 Infusion results

The CPM also demonstrated good qualitative agreement with experimental infusion results. Fig. 6 highlights the flow front profile for a 90°/0° orientation test against profiles from the CPM and a more basic model that assumes isotropic, deformation-independent permeability properties within the fabric. It can be seen that the general flow behaviour is well captured by the CPM, since regions of high shear deformation (locations 5-8 in Fig. 5) correspond well with increased permeability and faster flow. This is supported by the quantitative results in Fig. 7, captured at different times throughout infusion. Although the CPM exhibits some variance from the experimental results, there is significant improvement over basic modelling with similar properties, particularly in reproducing the deformation-dependent flow behaviour.

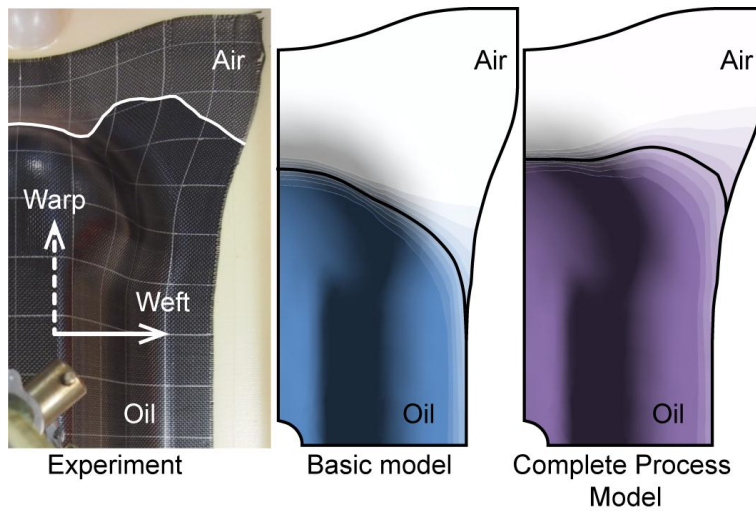


Figure 6: Simulated and experimental flow front comparison at 1255 seconds.

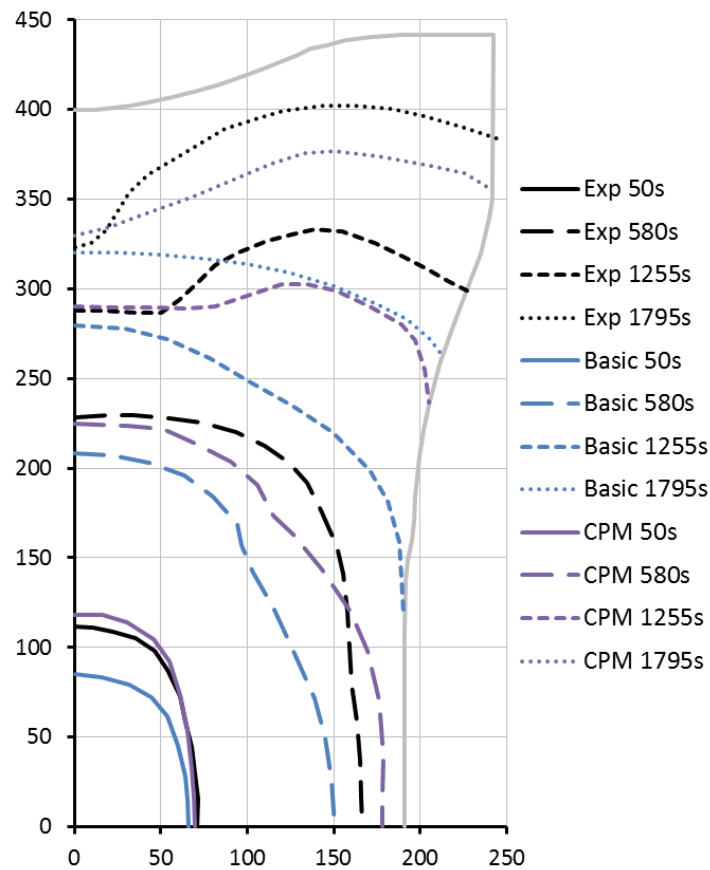


Figure 7: Transient flow front profiles from experimental and simulation results.

3.5 Multiple plies

Single ply simulations have provided a good demonstration of the CPM capabilities against the basic model that does not account for deformation effects on infusion. However, a single ply case is admittedly unrealistic for industrial application. Hence the CPM approach has been developed to ensure that realistic multiple-ply cases can also be studied, though for brevity (and without

experimental validation as yet) examples of multiple ply simulations have not been included in this paper.

8 DISCUSSION AND FUTURE POTENTIAL

These demonstration tests have shown that the CPM can provide great improvement over traditional models that neglect deformation-dependence. However, it is important to recognise that significant calibration of the permeability values was required (for both models), since the vacuum bagging configuration of the experimental double dome case differed from the rigid plate cavity of the permeability characterisation tests. Hence, it may be necessary to develop a more robust approach for characterising the permeability of samples under vacuum bag conditions in order to better reflect the true manufacturing process.

In general, there are a number of further improvements that can be made to the CPM. Fundamentally, the process of working with the CPM needs to be simplified before becoming viable for industrial applications. In particular, the wide range of software and coding languages employed in the various components of the CPM overcomplicate its use outside of academia. It may be possible to consolidate the full method into a single software suite such as ANSYS, which would also allow for greater automation and optimisation.

The realism of the Complete Process Model could also be extended and enhanced in several areas. For example, an improved structural analysis of the predicted part performance could be added to the end of the current model, accounting for local fibre orientations and fibre volume fraction. Alternatively, the curing reaction of the resin system could be included in the infusion model to account for exothermic effects and predict flaws such as partial curing. Void formation and transportation can also be modelled [19, 20], in order to better estimate final part saturation. Most importantly though, compaction behaviour and its effect on flow properties [21] could be included in the CPM and would help produce more accurate results.

9 CONCLUSION

This work to develop a Complete Process Model (CPM) for simulating Liquid Composite Moulding (LCM) processes with textile reinforcement materials combines research efforts from a number of different fields. Aerospace grade carbon fibre fabric samples have been experimentally characterised to find tensile, shear and permeability properties using advanced techniques. These properties support the material definitions in a continuum-based finite element draping model and a volume of fluids infusion model. Major novelty is achieved by linking the results of the draping model with the infusion model, such that the characterised relationship between shear deformation and fabric permeability helps to define a complex distribution of permeability properties throughout the preform prior to infusion.

The CPM has been evaluated against vacuum infusion experiments for a complex double dome part and shown good agreement. Material draw-in and shear deformation results predicted by the CPM were very accurate. Furthermore, the CPM infusion simulations reflected the true flow behaviour well, particularly in areas of high shear deformation and localised flow. Comparisons against traditional models, which do not account for deformation-dependent flow effects, show the CPM to be superior.

Ultimately, this work demonstrates the success of the Complete Process Model, and identifies the potential for future improvements to enhance realism and industrial viability.

ACKNOWLEDGEMENTS

This research was supported under the Australian Research Council's 'Linkage Projects' funding scheme (LP100100508) in partnership with Boeing Research & Technology Australia. The second

author would also like to acknowledge the financial support of Bombardier and the Royal Academy of Engineering.

REFERENCES

- [1] P. Boisse, A. Gasser and G. Hivet, Analyses of fabric tensile behaviour: determination of the biaxial tension-strain surfaces and their use in forming simulations, *Composites: Part A*, **32**, 2001, pp. 1395-414.
- [2] J. Cao, R. Akkerman, P. Boisse, J. Chen, H.S. Cheng, E.F. de Graaf, et al., Characterization of mechanical behaviour of woven fabrics: Experimental methods and benchmark results, *Composites: Part A*, **39**, 2008, pp. 1037-53.
- [3] P. Harrison, F. Abdiwi, Z. Guo, P. Potluri and W.R. Yu, Characterising the shear-tension coupling and wrinkling behaviour of woven engineering fabrics, *Composites: Part A*, **43**, 2012, pp. 903-14.
- [4] P. Potluri, D.A. Perez Ciurezu and R.B. Ramgulam, Measurement of meso-scale shear deformations for modelling textile composites, *Composites: Part A*, **37**, 2006, pp. 303-14.
- [5] R.S. Pierce, B.G. Falzon, M.C. Thompson and R. Boman, A low-cost digital image correlation technique for characterising the shear deformation of fabrics for draping studies, *Strain*, (in press), 2015 (doi: 10.1111/str.12131).
- [6] G. Lebrun, M.N. Bureau and J. Denault, Evaluation of bias-extension and picture-frame test methods for the measurement of intraply shear properties of PP/glass commingled fabrics, *Composite Structures*, **61**, 2003, pp. 341-52.
- [7] B. Zhu, T.X. Yu and X.M. Tao, Large deformation and slippage mechanism of plain woven composite in bias extension, *Composites: Part A*, **38**, 2007, pp. 1821-8.
- [8] R.S. Pierce, B.G. Falzon, M.C. Thompson and R. Boman, Contributions to the process modelling of resin infusion under flexible tooling (RIFT) manufacturing for composite aerostructures, *Proceedings of the 19th International Conference on Composite Materials ICCM19, Montreal, Canada, July 28th – August 2nd, 2013*, Montreal, 2013.
- [9] R. Arbiter, J.M. Beraud, C. Binetruy, L. Bizet, J. Bréard, S. Comas-Cardona, et al., Experimental determination of the permeability of textiles: A benchmark exercise. *Composites: Part A*, **42**, 2011, pp. 1157-68.
- [10] S. Sharma and D.A. Siginer, Permeability measurement methods in porous media of fiber reinforced composites, *Applied Mechanics review*, **63**, 2010.
- [11] C.C. Wong, A.C. Long, M. Sherburn, F. Robitaille, P. Harrison and C.D. Rudd, Comparisons of novel and efficient approaches for permeability prediction based on the fabric architecture, *Composites: Part A*, **37**, 2006, pp. 847-57.
- [12] F. Loix, P. Badel, L. Orgéas, C. Geindreau and P. Boisse, Woven fabric permeability: From textile deformation to fluid flow mesoscale simulations, *Composites Science and Technology*, **68**, 2008, pp. 1624-30.
- [13] A. Endruweit and P. Ermanni, The in-plane permeability of sheared textiles. Experimental observations and a predictive conversion model, *Composites: Part A*, **35**, 2004, pp. 439-51.
- [14] J. Slade, E.M. Sozer and S.G. Advani, Fluid impregnation of deformed preforms. *Journal of Reinforced Plastics and Composites*, **19** (07), 2000, pp. 552-68.
- [15] M.A. Khan, T. Mabrouki, E. Vidal-Sallé and P. Boisse, Numerical and experimental analyses of woven composite reinforcement forming using a hypoelastic behaviour. Application to the double dome benchmark, *Journal of Materials Processing Technology*, **210**, 2010, pp. 378-88.
- [16] X. Peng and Z.U. Rehman, Textile composite double dome stamping simulation using non-orthogonal constitutive model, *Composites Science and Technology*, **71**, 2011, pp. 1075-81.
- [17] P. Šimáček and S.G. Advani, Desirable features in mold filling simulations for liquid composite molding processes, *Polymer Composites*, **25**(4), 2004, pp. 355-67.

- [18] F.F. Luz, S.C. Amico, J.A. Souza, E.S. Barbosa and A.G. Barbosa de Lima, *Resin Transfer Molding Process: Fundamentals, numerical computation and experiments*. Numerical analysis of heat and mass transfer in porous media: Springer; 2012. p. 121-50.
- [19] E. Ruiz, V. Achim, S. Soukane, F. Trochu and J. Bréard, Optimisation of injection flow rate to minimize micro/macro-voids formation in resin transfer molded composites, *Composites Science and Technology*, **66**, 2006, pp. 475-86.
- [20] C.H. Park, A. Lebel, A. Saouab, J. Bréard and W.I. Lee, Modeling and simulation of voids and saturation in liquid composite molding processes, *Composites: Part A*, **42**, 2011, pp. 658-68.
- [21] Q. Govignon, S. Bickerton and P.A. Kelly, Simulation of the reinforcement compaction and resin flow during the complete resin infusion process, *Composites: Part A*, **41**, 2010, pp. 45-57.
- [22] S.V. Lomov, G. Huysmans, Y. Luo, R.S. Parnas, A. Prodromou, I. Verpoest, et al., Textile composites: modelling strategies, *Composites: Part A*, **32**, 2001, pp. 1379-94.
- [23] B. Verleye, S.V. Lomov, A. Long and D. Roose, Permeability prediction for the meso-macro coupling in the simulation of the impregnation stage of Resin Transfer Moulding, *Composites: Part A*, **41**, 2010, pp. 29-35.
- [24] ASTM D5035-11: Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Strip Method). *ASTM International*, 2011.
- [25] R.S. Pierce, Video processing for permeability characterisation - File exchange - MATLAB central (webpage), *The MathWorks, Inc.*, 2014.